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Radiation Dosimetry of an Accidental Overexposure using EPR Spectrometry and Imaging of Human Bone

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On 11 December 1991 a radiation accident occurred at an industrial accelerator facility. A description of the facility and details of the accident are reported in Schauer *et al.*, 1993a). In brief, during maintenance on the lower window pressure plate of a 3 MV potential drop accelerator, an operator placed his hands, head, and feet in the radiation beam. The filament voltage of the electron source was turned 'off', but the full accelerating potential was on the high voltage terminal. The operator's body, especially his extremities and head, were exposed to electron dark current. At approx. 3 months post-irradiation, the four digits of the victim's right hand and most of the four digits of his left hand were amputated. Electron paramagnetic resonance (EPR) spectrometry was used to estimate the radiation dose to the victim's extremities. Extremity dose estimates ranged from 55.0 Gy ($\pm$4.7 Gy) to 108 Gy ($\pm$24.1 Gy).

Introduction

On 11 December 1991 an accelerator operator at an industrial facility in Maryland was overexposed to radiation (Schauer *et al.*, 1993a). The radiation source was a 3 MV potential drop accelerator designed to produce high electron beam currents for radiation processing applications. This accelerator is capable of producing a 25 mA swept electron beam that emerges from the accelerator vacuum system through a titanium double window assembly. During maintenance on the lower window pressure plate, an operator placed his hands, head, and feet in the radiation beam. This was done with the filament voltage of the electron source turned 'off', but with the full accelerating potential on the high voltage terminal. This resulted in the operator being exposed to electron dark current. Dose rates measured during accident reconstructions ranged from approximately 40 cGy s^{-1} inside the victim's shoe to 1300 cGy s^{-1} at the hand position. About 3 months after the accident, digits from both of the victim's hands were amputated.

Personnel dosimetry devices were not worn by the victim. Electron paramagnetic resonance (EPR) spectrometry was therefore used in a post-irradiation study to estimate the victim's extremity dose. EPR dosimetry has been used to estimate personnel doses from the Chernobyl accident (Ishii *et al.*, 1990), and to estimate doses from the San Salvador accident (Desrosiers, 1991).

The principle of EPR spectroscopy is based on the resonant absorption of electromagnetic energy by paramagnetic species due to transition of the spin of an unpaired electron from one energy level to the next in the presence of a strong magnetic field. The EPR method using bone or tooth enamel takes advantage of the fact that radiation interacts with hydroxyapatite to produce concentrations, known to be linearly proportional to the absorbed radiation dose, of a long-lived paramagnetic center that is derived from the irradiated crystalline matrix. A series of known additive doses of ^{60}Co gamma rays are delivered to bone samples, and the EPR spectra are measured at each dose increment. By plotting the EPR signal amplitude as a function of these additive doses, the unknown accident dose can be estimated by extrapolation (curve fitting) of the generated linear response curve to the abscissa (absorbed dose scale).

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Copeland *et al.* (1993) reported that the EPR signal intensity per unit dose from irradiated ovine cortical bone is fairly constant with electron energy in the range 2–10 MeV, and approximately equal to that at a photon energy of 1.25 MeV. Since the accident dose was from approx. 1.5 MeV electrons, and ^{60}Co gamma rays would be used to obtain EPR dose estimates, we measured the radiation-induced EPR signal intensities from human donor cortical bone samples irradiated with essentially mono-energetic

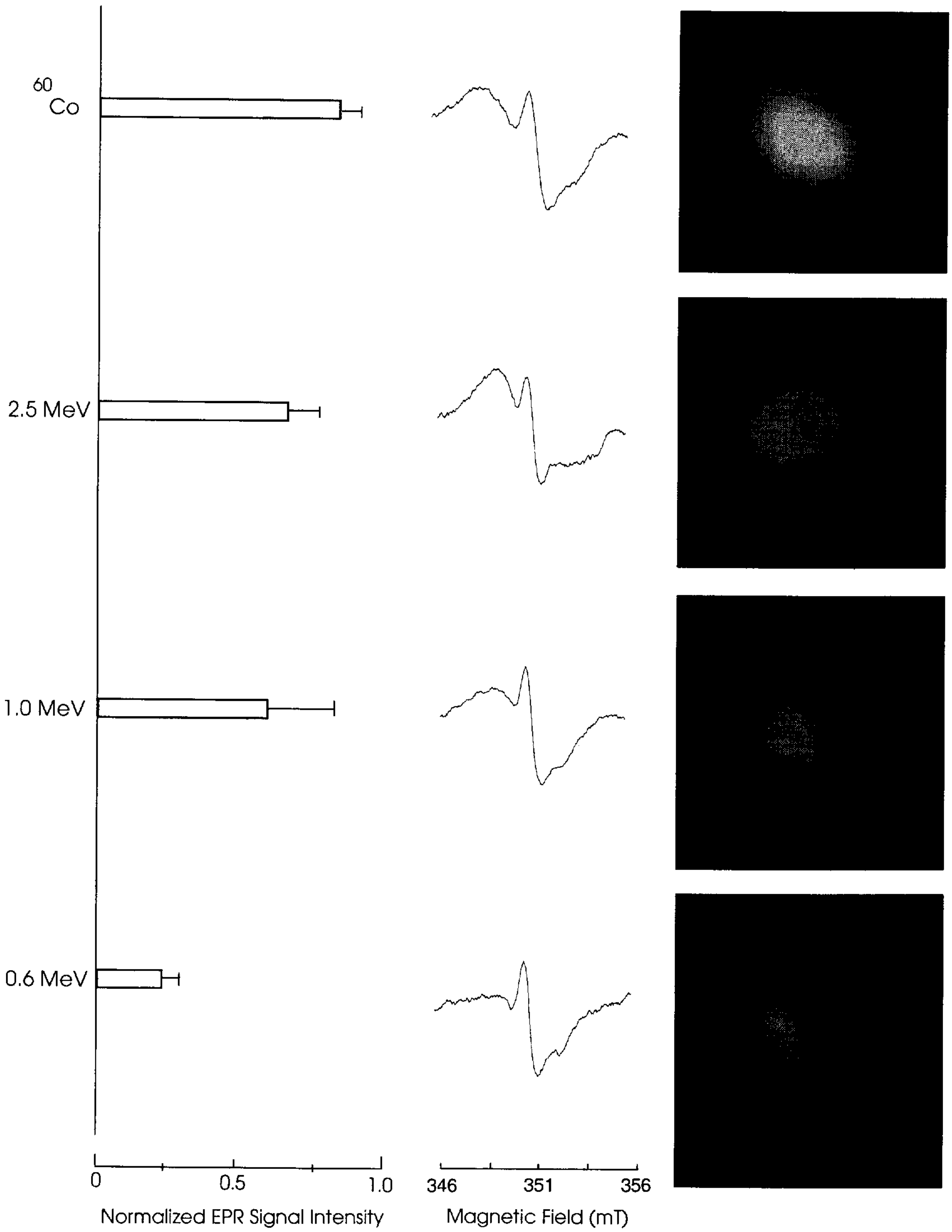

Fig. 1. Mean-normalized EPR signal intensities for human cortical bone samples irradiated to an absorbed dose of 50 Gy with 0.6, 1.0, and 2.5 MeV electrons, and ^{60}Co gamma rays (horizontal bars represent one half of the 95% confidence interval). Included are the first derivative absorption spectra with respect to the applied magnetic field, and two-dimensional spatial cross sectional EPR images (10 mm × 10 mm) for one bone from each group.

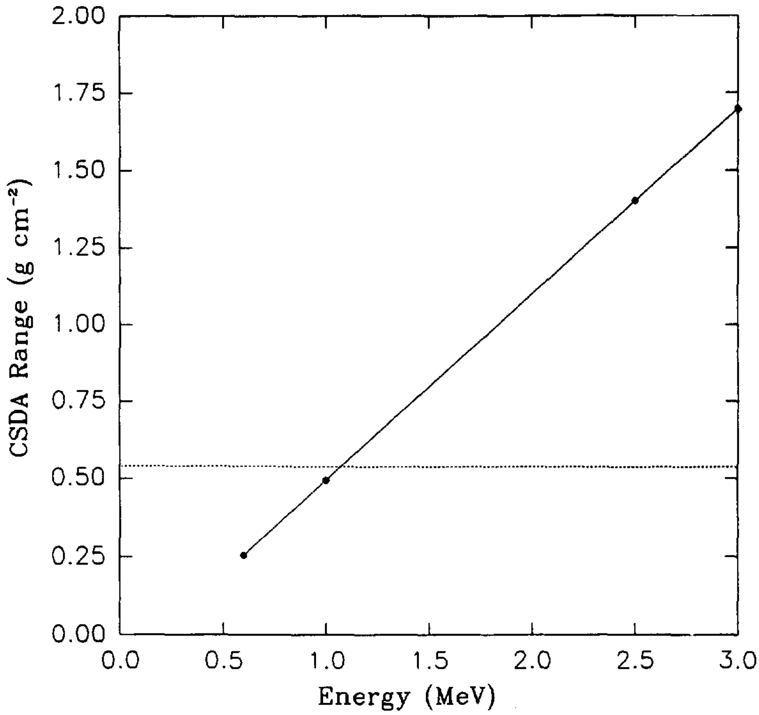

Fig. 2. Continuous-slowing-down-approximation (CSDA) range in g cm^{-2} as a function of electron energy for ICRU44 human adult cortical bone. The range of bone thicknesses used in this study was 0.38–0.58 g cm^{-2} (the maximum thickness is indicated by the dashed rule).

0.6, 1.0 and 2.5 MeV electrons, and with ^{60}Co gamma rays. The results of this experiment, and 2-dimensional spatial cross sectional EPR images for one bone sample from each group are reported along with dose estimates to the victim's extremities.

Experimental*

Human cortical bone samples from a donated human tibia were prepared with a low-speed diamond blade saw. Sample dimensions were approx. 2–3 mm (0.38–0.58 g cm^{-2}) in diameter and 25 mm in length, and the average mass was 144 mg. The National Institute of Standards and Technology (NIST) 4 MV Van de Graaff cascaded accelerator was used to generate nearly mono-energetic electron beams of 0.6, 1.0, and 2.5 MeV (Soares *et al.*, 1985). Photon irradiations were conducted using the vertical beam of the NIST ^{60}Co teletherapy source. Four different bone samples were used to study each type and energy of radiation. Dosimetry for the electron beam irradiations was performed with GafChromic™ film (McLaughlin *et al.*, 1991), and ionization chambers were used for the ^{60}Co measurements (Schauer *et al.*, 1993b). The EPR spectra were recorded with an X-band Bruker ESP300E spectrometer equipped with a transverse magnetic (TMH) resonator. Typical settings were microwave power 160 mW, modulation amplitude 0.2 mT, and modulation frequency 100 kHz.

EPR images were acquired at The Johns Hopkins University EPR Laboratories with an X-band spectrometer. This system has been described in detail (Kuppusamy *et al.*, 1994).

Bone samples from the victim's digits were provided by the hand surgeon. These samples were cut with a diamond blade saw, and air dried.

Results and Discussion

The first column of Fig. 1 is a plot of mean-normalized EPR signal intensities with the upper 95 % confidence interval for human donor bone samples irradiated with 0.6, 1.0, and 2.5 MeV electrons, and with ^{60}Co gamma rays to an absorbed dose of 50 Gy. The second column consists of the first-derivative absorption spectrum with respect to the applied magnetic field for one bone from each group.

One-way analysis of variance (ANOVA) of the EPR signal intensities derived from these different radiations yielded an F-statistic of 66.0 and the critical value was 3.49 at the $\alpha = 0.05$ level. There is sufficient evidence to conclude that there is a statistically significant difference among the EPR signal intensities from these different radiations. Newman–Keuls multiple comparisons were then used

*Mention of commercial products does not imply recommendation or endorsement by the NIST, nor does it imply that the products identified are necessarily the best for the purpose.

to identify the differences. A statistically significant difference at the $\alpha = 0.05$ level was found between the 0.6 MeV values and all others. However, there was no statistically significant difference among the 1.0 MeV, 2.5 MeV electrons, and ^{60}Co gamma-ray values.

The difference between the 0.6 MeV values and all others can be explained by Fig. 2, which is a plot of the continuous slowing down approximation (CSDA) range as a function of electron energy for the International Commission on Radiation Units and Measurements (ICRU) Report No. 44 composition of human adult cortical bone. The CSDA range is greater than the bone thicknesses used in this study for all energies, except 0.6 MeV. In fact, the bone thickness is approximately a factor of two greater than the CSDA range for 0.6 MeV electrons resulting in a nonuniform irradiation. This is consistent with the normalized EPR signal intensity for this energy being approximately a factor of two less than the EPR signal intensities for the other radiations.

If the lower EPR signal intensity for the 0.6 MeV electron-irradiated bones is due to a nonuniform irradiation, this should be evident on EPR images of the bones. Column 3 of Fig. 1 shows 2-dimensional spatial cross-sectional EPR images of one bone sample from each group. The images of the bones irradiated with radiation that has a range greater than the sample thickness show a relatively uniform distribution of paramagnetic centers. However, the centers are concentrated on one side of the 0.6 MeV bone sample. This observation is consistent with the electron range data.

We have shown that the radiation-induced EPR signal intensity derived from the crystalline matrix of human cortical bone is independent of the type and energy of radiation for 0.6 to 2.5 MeV electrons and ^{60}Co, provided the sample thickness is not greater than the range of the radiation. This finding shows that ^{60}Co can be used to generate EPR dose estimates when the dose in question is from a different type and energy radiation. We have also used EPR imaging to show, in two-dimensions, the effect of using a bone sample thickness that is greater than the range of the radiation.

As shown by the example in Fig. 3, the dose estimate for bones from the victim's digits can be determined using least-squares linear regression extrapolated in this case to an accident dose of 108 Gy. The dose estimates for all the tested bones of the victim's left-hand digits ranged from 55 Gy ($\pm$ 4.7 Gy) to 108 Gy ($\pm$ 24.1 Gy) (error estimates are quoted as the standard deviation, 2 σ, of the extrapolated dose) (Fig. 4). These dose estimates are consistent with the tissue damage observed (Schauer *et al.*, 1993a). Due to the nature of the surgical procedure performed on the victim's right hand, the bone samples obtained were not suitable for EPR

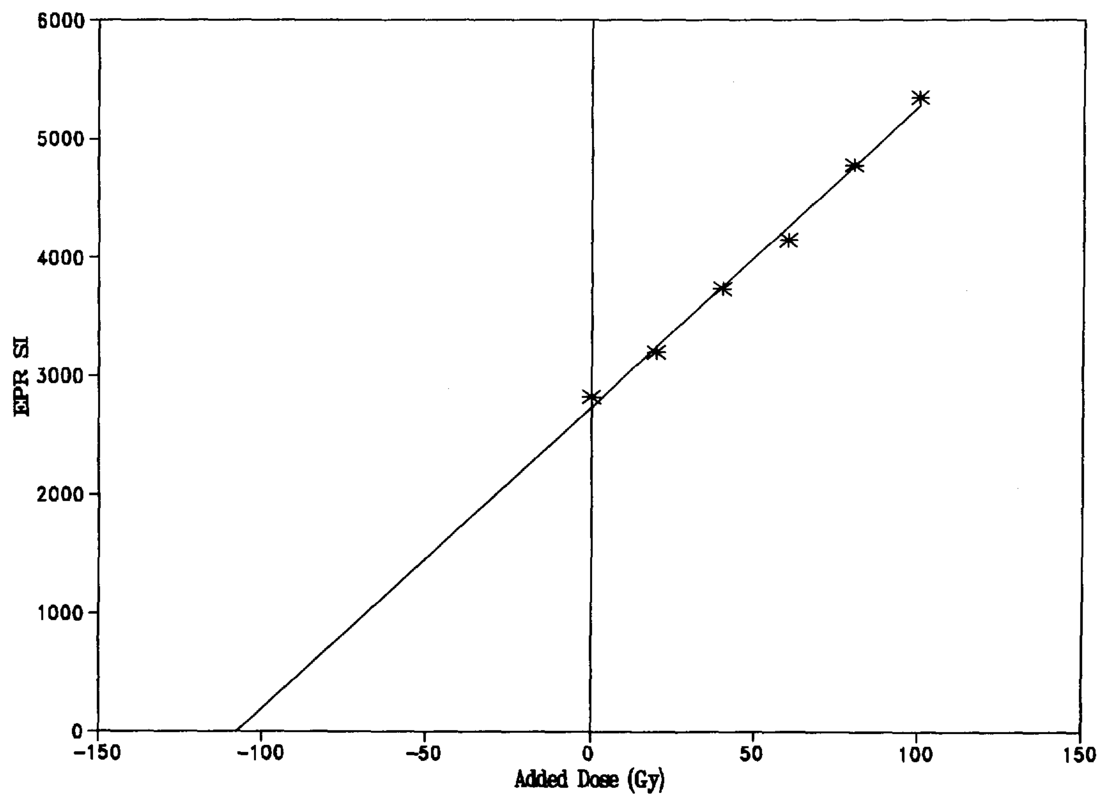

Fig. 3. Least-squares linear regression fit to data for the left index finger, distal phalanx extrapolated to an accident dose of 108 Gy.

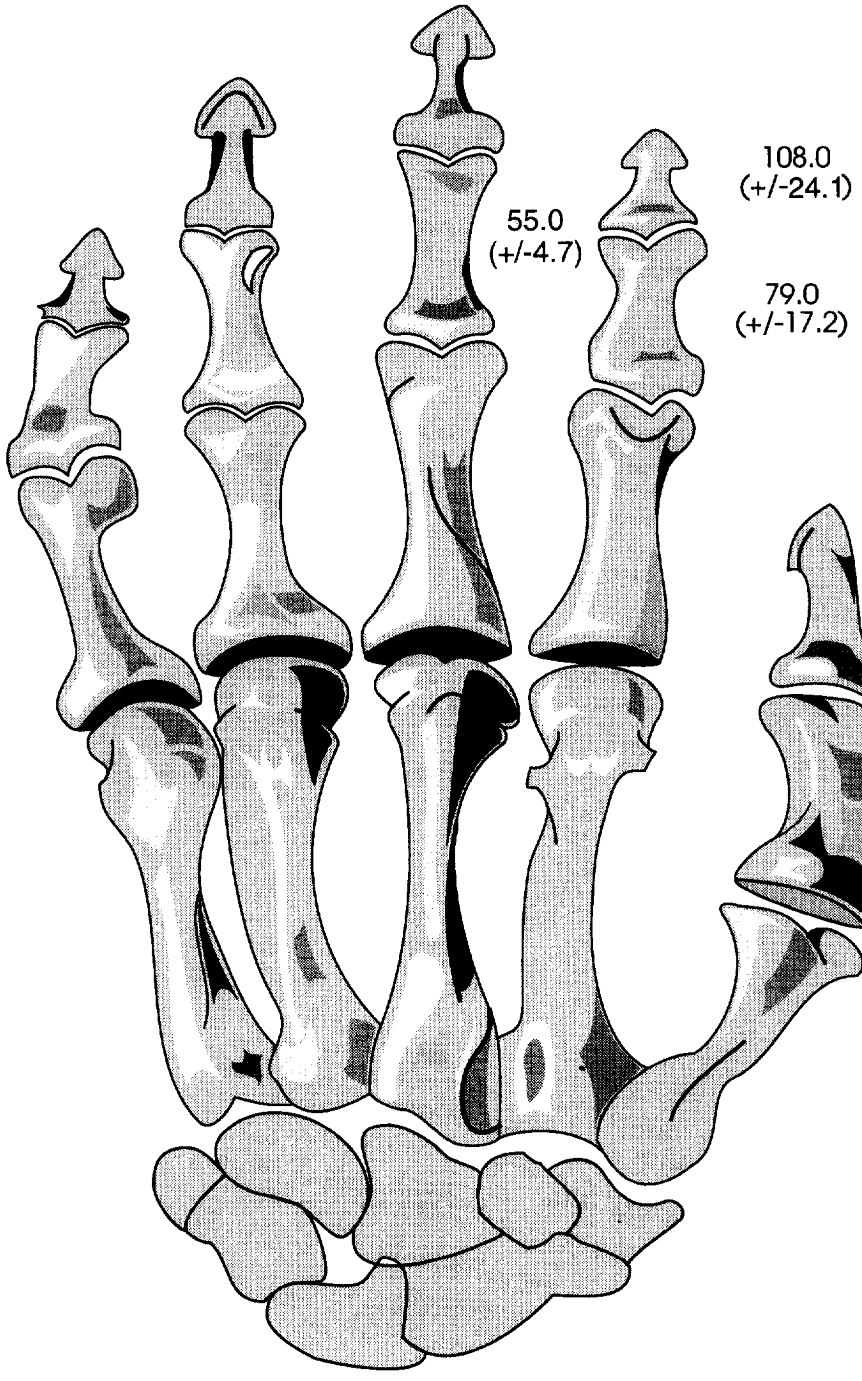

Fig. 4. Skeleton of the left hand with the dose estimates assigned to the three bones measured, according to EPR dosimetric estimates.

dosimetry. As a final note, since the exposure was localized, cytogenetic blood tests were not successful in determining whether the victim received a significant dose; however, the dose estimates obtained by EPR bone dosimetry were consistent with the details of the accident as carried out with a reconstruction using calibrated alanine and radiochromic film dosimeters (Schauer *et al.*, 1993a).

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